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| 1. Your reference | IP/P7284 | | |
| 2. Patent application number *(The Patent Office will fill in this part)* | 0315526.4 | | 03 JUL 2003 |
| 3. Full name, address and postcode of the or of each applicant *(underline all surnames)* | QINETIQ LIMITED<br>Registered Office 85 Buckingham Gate<br>London SW1E 6PD<br>United Kingdom | | |
| Patents ADP number *(if you know it)*<br>If the applicant is a corporate body, give the country/state of its incorporation | GB 8183857001 | | |
| 4. Title of the invention | THERMAL DETECTOR | | |
| 5. Name of your agent *(if you have one)* | P DAVIES et al | | |
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| Patents ADP number *(if you know it)* | 8183873005 | | |
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| Abstract | 1 |
| Drawing*(s)* | 8 + 8 |

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| Priority documents | 0 |
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| Request for substantive examination *(Patents Form 10/77)* | 0 |
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11. I / We request the grant of a patent on the basis of this application.

Signature PHILIP DAVIES    Date 1.7.03

12. Name and daytime telephone number of person to contact in the United Kingdom    Linda Bruckshaw 01252 392722

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Thermal Detector

The present invention relates to an uncooled thermal detector and in particular to a radiant thermal energy detector incorporating a micro-electromechanical system (MEMS) resonant structure.

All objects emit radiation with an intensity and wavelength distribution that is determined by their surface temperature and character. For objects (such as human bodies) around room temperature the emitted energy peaks in the infra-red. As the infra-red radiation is related to the temperature of an object, it is often referred to as thermal infrared radiation.

A number of types of thermal detector (sometimes called bolometers or infra-red detectors) are known. Typical detectors comprise a number of detection elements (or pixels) each comprising a thin layer of material having properties that change with temperature. Any infra-red radiation absorbed by the layer of temperature sensitive material causes heating thereof. It is common for the associated change in material properties to be measured by monitoring changes in the resistance or capacitance of a pixel. The detection elements are typically thermally isolated from the substrate; for example in a micro-bridge arrangement.

A typical temperature sensitive material used in a resistive bolometer exhibits resistance changes of around 1-2% per Kelvin. Typical performance for a commercially available Vanadium Oxide resistive bolometer is of the order of 60mK NETD (Noise Equivalent Temperature Difference) at around 30Hz frame rate with a pixel pitch of approximately 50μm and F1 optics. The performance of resistive thermal detectors is generally limited by the detector Johnson noise, and the subsequent signal to noise ratio associated with the detector and read-out circuit. Research has thus been undertaken in recent years directed to developing materials which exhibit larger changes in material properties with temperature.

One known technique for increasing thermal detector sensitivity (i.e. increasing the change in material properties for a given temperature variation) is to use colossal magneto-resistive or CMR materials, such as LCMO ($La_{0.7}Ca_{0.3}MnO_3$) in which a rapid phase change leads to large changes in properties. Such an approach has several drawbacks. CMR materials tend to be incompatible with standard CMOS processing. This makes integration of the detector and associated electronic read-out circuitry more difficult and relying on a sudden phase change limits the flexibility of the resulting detector. At operating temperatures away from the phase change the material is insensitive to changes in temperature, and the temperature range over which the phase change occurs is a property of the material, and as such cannot easily be tailored to best meet the requirements of a detector.

Various alternative thermal detector arrangements have also been described in the prior art. For example, it is known to exploit a thermo-mechanical effect to change the capacitance of a pixel. US6392233 describes a thermal detector comprising bimorph cantilevers which change the position of a pixel relative to the substrate with temperature thereby altering the capacitance of the pixel. The measurement of the resulting capacitance is at base band (DC) and performance is therefore limited by subsequent 1/f noise in CMOS circuitry.

MEMS devices are also known, outside the field of thermal imaging, and have been widely used in inertial devices such as gyroscopes and accelerometers. It is known that the resonant frequency of a MEMS device will change with temperature, but generally MEMS devices have been designed to minimise such temperature dependent effects. US5772322 describes a MEMS resonant structure that may be used to measure temperature. The device of US5772322 comprises a resonant beam structure formed on a substrate. The substrate and resonant beam structure are heated and, due to the different thermal expansion coefficient of the beam and substrate, the resonant frequency of the beam changes.

It is an object of the present invention to mitigate at least some of the aforementioned disadvantages of known infra-red detector devices.

According to a first aspect of the invention, a thermal detector comprises one or more detection elements for receiving infra-red radiation, each detection element comprising a temperature sensing region located on a suspended portion spaced apart from the underlying substrate of the thermal detector, characterised in that the temperature sensing region comprises a resonator element having a resonant property that varies with temperature.

Advantageously, the resonant property of the resonator element that varies with temperature is the resonant frequency. Measurement of the resonant frequency of the resonator element can then provide an indication of temperature.

Alternatively, the mechanical resonator may conveniently be arranged such that its mode shapes change with temperature. This may be achieved by preferential heating of part of a temperature sensitive resonator. Changing the mode shapes of a well balanced resonator in this way lead to changes in the mechanical quality factor, Q, of the resonator modes which may be monitored to provide an indication of temperature.

A thermal detector of the present invention is advantageous for several reasons: it can be arranged to have a very high dynamic range and/or sensitivity; it circumvents the noise issues associated with taking base-band measurements; it can be readily post-processed onto CMOS. The dynamic range and sensitivity of a detection element of the present invention may also be controlled by appropriate design and fabrication of the pixel. This should be contrasted to prior art devices comprising temperature sensitive materials where layers of an alternative material would have to be deposited in order to significantly alter the dynamic range and/or sensitivity of the device.

Furthermore, and unlike prior art detectors, the detector of the present invention is not reliant on the measurement of the relative resistance or capacitance of a layer of temperature sensitive material with temperature. Instead, the output is derived from

measurement of the change imparted to the resonant mode of a resonator element when a temperature variation is induced therein by the absorption of infra-red radiation. Measuring a change in the resonant mode (e.g. measuring a change in resonant frequency) is generally more accurate than making relative resistance of capacitance measurements.

Locating the temperature sensing region on the suspended portion ensures substantial thermal isolation of the temperature sensing region from the underlying substrate of the device. The precise amount of thermal isolation required to provide a device that can operate at a certain frame rate depends on the thermal capacity of the suspended portion and the required sensor performance.

It should be noted that if the resonant element was formed such that it was a integral part of the underlying substrate, the poor thermal isolation of the arrangement would prevent operation as a thermal detector; i.e. the heating induced by the thermal radiation would be insufficient to significantly alter the temperature of the poorly thermally insulated detector element. In other words a temperature sensing resonant structure of the type described in US5772322 could not operate as a thermal detector due to its low thermal isolation.

Advantageously, an output is provided by each detector element that is indicative of the resonant frequency of the resonator element. For example, further electronics may be included within the pixel to provide a base band output from each detector element that is indicative of the resonant frequency (and hence the temperature) of the resonator element.

Conveniently, a plurality of detection elements are provided. For example, a two dimensional array of detection elements may advantageously be provided. The two dimensional array may comprise at least 16 by 16, 32 by 32, 64 by 64, 128 by 128, 256 by 256 etc detection elements.

Each detection element may conveniently further comprise oscillation means to drive the resonator element into resonance. This can provide an electrical oscillator with the mechanical resonator element acting as the primary component determining frequency. The oscillation drive means may conveniently comprise an electrode on said underlying substrate to electrostatically drive the resonator element. The oscillation drive means may alternatively comprise a piezoelectric actuation means on the resonator element. Monitoring the frequency of the resulting electrical oscillator allows the temperature of the pixel to be inferred.

Conveniently, the suspended portion is suspended from the underlying substrate on at least one leg. Preferably, two legs are provided to support the suspended portion. The legs may advantageously include conductive material to provide an electrical connection from the resonator to the fixed metal layer. The suspended portion may include an absorber layer (e.g. a metal absorber layer such as titanium) designed to maximise the amount of incoming radiant energy absorbed as heat into the detector. The absorber layer may perform both absorber and electrical connection roles in combination.

Advantageously, the resonator element comprises at least one flexible elongate beam. For example, the temperature sensing region may conveniently comprise a layer in which an aperture is defined, said flexible beam being arranged to lie across the aperture and being fixed at two points to the edge of said layer defining the aperture. In the case of an electrostatic oscillation means, the flexible beam can then be driven to resonate by an electrode fixed on the substrate below the suspended beam.

Preferably, the flexible beam and the layer in which the aperture is formed have different coefficients of thermal expansion. Heating the suspended portion (i.e. the layer in which the aperture is formed and the flexible beam) thus results in a change in the axial stress applied to the flexible beam. This change in stress alters the resonant frequency of the flexible beam.

In the case of an electrostatic oscillation means the flexible beam may advantageously comprise a layer of conducting or semiconducting material, such as polysilicon or aluminium. In the case of a piezoelectric drive means the flexible beam may comprise a composite of conductors, semiconductors and piezoelectric materials. The layer in which the aperture is defined may conveniently comprise a metal, semiconductor or dielectric. Furthermore, the flexible beam and/or the layer in which an aperture is formed may comprise a shape memory alloy.

For ease of manufacture, it is preferred that the resonator element is formed using a micro-electromechanical system (MEMS) fabrication process. A thermal detector of the present invention can advantageously be manufactured using many of the numerous MEMS fabrication techniques that are known to those skilled in the art. For example, metal-nitride sacrificial surface micromachining as described by R.R. Davies, K.M. Brunson, M. McNie, D. J. Combes in "Engineering In- and Out-of-Plane stress in PECVD Silicon Nitride for CMOS-Compatible Surface Micromachining", SPIE Microfabrication and Micromachining Oct 2001, California, USA is one example of a technique suitable for manufacturing such a detector.

To optimise performance, it is advantageous for the thermal mass of the suspended portion to be minimised, and for the thermal isolation of the suspended portion to be high, such that the temperature sensing region both approaches thermal equilibrium in the frame time of the detector and the temperature change in the pixel is maximised for a given amount of incoming radiation. To maximise the temperature sensitivity of the resonator element, it is advantageous that its thickness be small.

According to second aspect of the invention, a thermal imaging camera incorporates a thermal detector according to the first aspect of the invention. The thermal imaging camera would also comprises a housing, infra-red optics etc.

The invention will now be described, by way of example only, with reference to the accompanying drawings in which;

Figure 1 illustrates a prior art infra-red detector pixel,

Figure 2 shows a typical response curve of a prior art infra-red detector pixel of the type shown in figure 1,

Figure 3 shows a typical response curve of a prior art infra-red detector incorporating CMR material,

Figure 4 shows a MEMS resonator infra-red pixel of the present invention,

Figure 5 shows a schematic sectional view of a pixel according to the invention,

Figure 6 shows a schematic plan view of a pixel according to the invention,

Figure 7 shows three snap shot views of a MEMS resonator of the present invention during the oscillation process,

Figure 8 shows the calculated temperature versus resonant frequency response of a MEMS resonator of the present invention,

Figure 9 shows the calculated frequency sensitivity versus temperature response of a MEMS resonator of the present invention,

Figure 10 shows an example of a mask design for four pixel detectors of the present invention, and

Figure 11 shows a thermal imaging camera incorporating a detector of the present invention.

Referring to figure 1, a pixel 2 of a typical prior art infra-red detector is shown. In particular, figure 1a shows a plan view, and figure 1b a side view, of the pixel 2. The

pixel 2 includes a suspended portion 4 that comprises a temperature sensitive layer and an absorber layer. The suspended portion 4 is mounted on an underlying substrate 8 via a pair of legs 11 and contact holes 10 thereby ensuring the suspended portion 4 is substantially thermally isolated from the underlying substrate 8. Electrodes 12 are also provided to allow electrical connection to and from the pixel.

In use, thermal radiation is absorbed by the absorber layer which causes heating thereof. The increase in temperature is transferred throughout the suspended portion, and alters the material properties of the temperature sensitive layer producing a measurable change in the resistance and/or capacitance of the pixel.

Referring to figure 2, an illustration of the response curve of a prior art detector material of a relax-ferroelectric type is given. It can be seen that the variation in material properties (typically measured as a change in pixel resistance or capacitance) varies over the operational range but that temperature sensitivity is typically limited to around 1% per Kelvin.

Referring to figure 3, an illustration of the response curve of a prior art detector material of a CMR type is given. It can be seen that the variation in material properties is very marked over a small operational range, with sensitivities in excess of 30% per Kelvin. Away from this narrow temperature range, temperature sensitivity is less marked. It can be seen that the temperature region over which the material is most sensitive is not commensurate with typical ambient conditions.

Referring to figure 4, an infra-red detector pixel 30 of the present invention is shown. The pixel 30 includes a suspended portion 32 comprising a dielectric layer in combination with an absorber layer, in which a hole 34 is formed. An elongate metallic resonator beam 36 is placed across the hole 34. Via contact holes are cut to electrically connect the resonator beam 36 with the fixed metal layer 35 via the legs 43. In order to maximise thermal isolation between the suspended portion 32 and the substrate 40, the legs 43 are long and thin.

Referring now to figures 4, 5 and 6 a process by which a detector according to the invention may be realised is outlined. The process comprises the steps outlined below:

(a) All layers are preferably fabricated on virgin silicon wafers, preferably supplied from a qualified major wafer supplier.

(b) An electrical isolation layer of silicon dioxide film 50 is grown/deposited on the wafers (i.e. the substrate 40). Contact holes may be etched (e.g. by reactive ion etching, RIE) in this layer to enable a bulk substrate contact to be made in subsequent process steps.

(c) A metal film 51 (METAL0) is deposited next (e.g. by sputter deposition), and is then patterned using photolithography. In this process, the wafers are coated with photoresist, the photoresist is exposed with the appropriate mask, and the exposed photoresist is developed to create the desired etch mask for subsequent pattern transfer into the underlying layer. After patterning the photoresist, the underlying layer is etched (e.g. by RIE). This sequence of lithography, deposition and etch is repeated to build up a "two and a half dimensional" structure on the surface of the wafer. This fixed metal layer 51 forms electrodes, interconnects and bond pads.

(d) A sacrificial layer 52 (such as polyamide, amorphous silicon etc) is then deposited (e.g. by resist spinning). This layer may provide a degree of planarisation, and is removed in a release process (such as a RIE release or wet etch release process) at the end of the fabrication process to free the suspended structural layers.

(e) Contact holes 53 are etched in the sacrificial layer, to enable electrical and mechanical connections between the moving mechanical layers and the fixed metal layer.

(f) A dielectric layer 54 (DIEL1), preferably of low thermal expansion co-efficient, is deposited (e.g. PECVD Silicon Nitride) and patterned (e.g. by RIE). VIA1, 62 is

cut in the layer to enable subsequent layers to contact METAL0, 51. This layer provides the bottom of a stress balanced, three layer mechanical composite for the suspended pixel. The layer is also preferably of low thermal conductivity and thermal mass.

(g) A thin metal layer 55 (METAL1) is deposited and patterned (e.g. sputtered Al, RIE). This layer is designed to ensure good contact between METAL3 and METAL0. It is convenient if the layer is insensitive to the process used to etch DIEL2.

(h) A thin absorber layer 56 (ABS) is deposited and patterned (e.g. sputtered Ti, RIE). This layer must be of low thermal conductivity, and is designed to both absorb incoming radiation and provide for electrical connection between METAL3 (60) and METAL0 (51) (via METAL1, 55). This layer forms the central layer of the three layer structural composite 57.

(i) A dielectric layer 58 (DIEL2) of identical material specifications to DIEL1 (54) is deposited and patterned. VIA2 (63) is cut in the layer to enable subsequent layers to contact ABS (56). This is the final layer of the three layer structural composite, and is necessary to balance any stress from DIEL1 (54).

(j) A metal 59 (METAL2) is deposited and patterned (e.g. sputtered Al, RIE). This layer is to ensure good contact down the anchor contact holes to METAL0.

(k) A metal 60 (METAL3) is deposited and patterned (e.g. sputtered Al, RIE). This metal is preferably of high thermal expansion co-efficient. This layer forms the mechanical resonator element 36 shown when released in figure 4.

(l) The sacrificial layer 52 is removed in a release process (such as an RIE release), to free the suspended mechanical layers.

It should be noted that the above example shows a device according to the invention with the main pixel structure formed of a material with low thermal expansion co-efficient, with the resonator being formed of a material with high thermal expansion co-efficient. A device according to the invention could function equally well the other way around i.e. with the main pixel structure formed from a material with high thermal expansion co-efficient and the resonator formed from a material with low thermal expansion co-efficient.

In the example given above, the dielectric layers DIEL1 and DIEL2 (54, 58) may comprise silicon nitride. METAL3 (60) may comprise aluminium. The thermal expansion co-efficients of silicon nitride and aluminium are approximately 2.5ppm/K and 24ppm/K respectively. Heat absorbed into the suspended portion, including the resonator will therefore lead to a mismatched expansion which in turn leads to a change in the tension in the beam. Changes in tension will lead to a change in the resonant frequency of the beam.

In order to maximise the temperature rise at the pixel it is necessary to minimise thermal conductance. This is achieved using the silicon nitride legs 43 to reduce the transfer of thermal energy from the suspended portion of the device to the substrate and also by operating the device in a vacuum to minimise heat loss through the atmosphere. Furthermore, the thermal time constant of the suspended portion of the pixel is preferably made small enough to approach equilibrium in the array read time.

It can be seen clearly from figure 5 that the process described allows for electrical connections via the fixed metal layer METAL0 (51) to the resonator and to a drive electrode 61 (formed from the metal layer 51) spaced on the substrate below the resonator.

In order to drive the beam into resonance, a varying electric field is applied between the resonator beam 36 (i.e. via the electrical connection provided by the METAL1 60 and ABS 56 layers down at least one of the legs 43) and a base electrode 61 that

is located on the substrate 40 directly below the resonator beam 36. The resonator 36 and drive electrode 61 form part of an electrical oscillator (not shown) with the mechanical resonator as the primary component determining frequency. Preferably the further electrical components comprising the electrical oscillator are located within the area of the pixel. Further electronics are advantageously located in the pixel to provide a base band output from the pixel dependant on the frequency of the electrical oscillator.

Referring to figure 6 the outline patterns used to define the layers, vias and contact holes given in the above example process are illustrated.

Referring to figure 7, three snapshot illustrations of the resonator beam 36 during the oscillation process are shown. In figure 7a, the resonator element is fully deflected upwards, in figure 7b the resonator beam is in a central position, whilst figure 7c shows the resonator beam fully deflected downwards.

In figure 8, the calculated resonant frequency of the resonator beam of a device described with reference to figure 4 is shown. Results from both an analytical model of the device and a finite element simulation are shown. Referring to figure 9, the calculated frequency sensitivity as a function of temperature for the same device is also shown. It can be seen from figures 8 and 9 that the frequency sensitivity of a device of the present invention can be made very high.

Referring to figure 10, a mask design for a four pixel infra-red detector of the present invention is shown. The mask comprises four pixels 70a-70d (collectively referred to as pixels 70), each having a nitride resonator beam 72 formed on a layer of aluminium. Each pixel is around 50μm wide. It can be seen from this figure, how the present invention allows thermal imaging arrays of multiple pixels to be made.

Figure 11 shows a thermal detector array 100 of the present invention incorporated into a thermal imaging camera 102 arranged to receive radiation from an object 104 in a scene. The device comprises infra-red optics 106 to collect thermal radiation

from the scene and to direct such radiation to the detector array 100. Electronic processing equipment 108 and a monitor 110 are also provided. The details of the precise arrangement of optics and control electronics etc in such a camera would be inherent to a person skilled in the art.

Claims.

1. A thermal detector comprising one or more detection elements for receiving infra-red radiation, each detection element comprising a temperature sensing region located on a suspended portion spaced apart from the underlying substrate of the thermal detector, characterised in that the temperature sensing region comprises a resonator element having a resonant property that varies with temperature.

2. A detector according to claim 1 wherein the resonant property that varies with temperature is resonant frequency.

3. A detector according to claim 2 wherein an output is provided by each detector element that is indicative of the resonant frequency of the resonator element.

4. A detector according to any preceding claim wherein a plurality of detection elements are provided.

5. A detector according to any preceding claim wherein a two dimensional array of detection elements are provided.

6. A detector according to any preceding claim wherein each detection element further comprises oscillation means to drive the resonator element into resonance.

7. A detector according to claim 6 wherein the oscillation means comprises an electrode on said underlying substrate to electrostatically drive the resonator element.

8. A detector according to claim 5 wherein the oscillation means comprises a piezoelectric drive means.

9. A detector according to any preceding claim wherein the suspended portion is suspended from the underlying substrate on at least one leg.

10. A detector according to claim 9 wherein the at least one leg comprises conductive material to provide an electrical connection between the suspended portion and the underlying substrate.

11. A detector according to any preceding claim wherein the resonator element comprises at least one flexible elongate beam.

12. A detector according to claim 11 wherein the temperature sensing region comprises a layer in which an aperture is defined, said at least one flexible elongate beam being arranged to lie across the aperture and being fixed at two points to the edge of said layer defining the aperture.

13. A detector according to claim 12 wherein the flexible beam and the layer in which the aperture is formed have different coefficients of thermal expansion.

14. A detector according to any one of claims 12 to 13 wherein the at least one flexible beam and/or the layer in which an aperture is formed comprise a shape memory alloy.

15. A detector according to any preceding claim that is formed using a micro-electromechanical system (MEMS) fabrication process.

16. A thermal imaging camera incorporating a detector according to any preceding claim.

17. A thermal detector as hereinbefore described with reference to any one of figures 4 to 10.

Abstract

## Thermal Detector

A thermal detector is described that comprises one or more detection elements (30) for receiving infra-red radiation. Each detection element has a temperature sensing region located on a suspended portion (32) spaced apart from the underlying substrate (40) of the thermal detector. The temperature sensing region comprises a mechanical resonator (36) element having a resonant property, such as resonant frequency, that varies with temperature.

Figure 4 refers

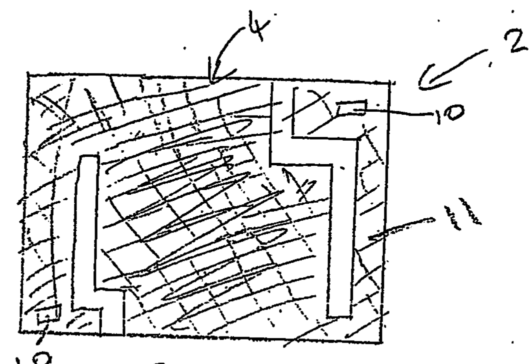


Fig 1a

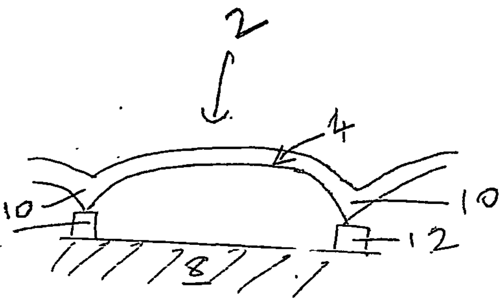


Fig 1b

**FIGURE 1**

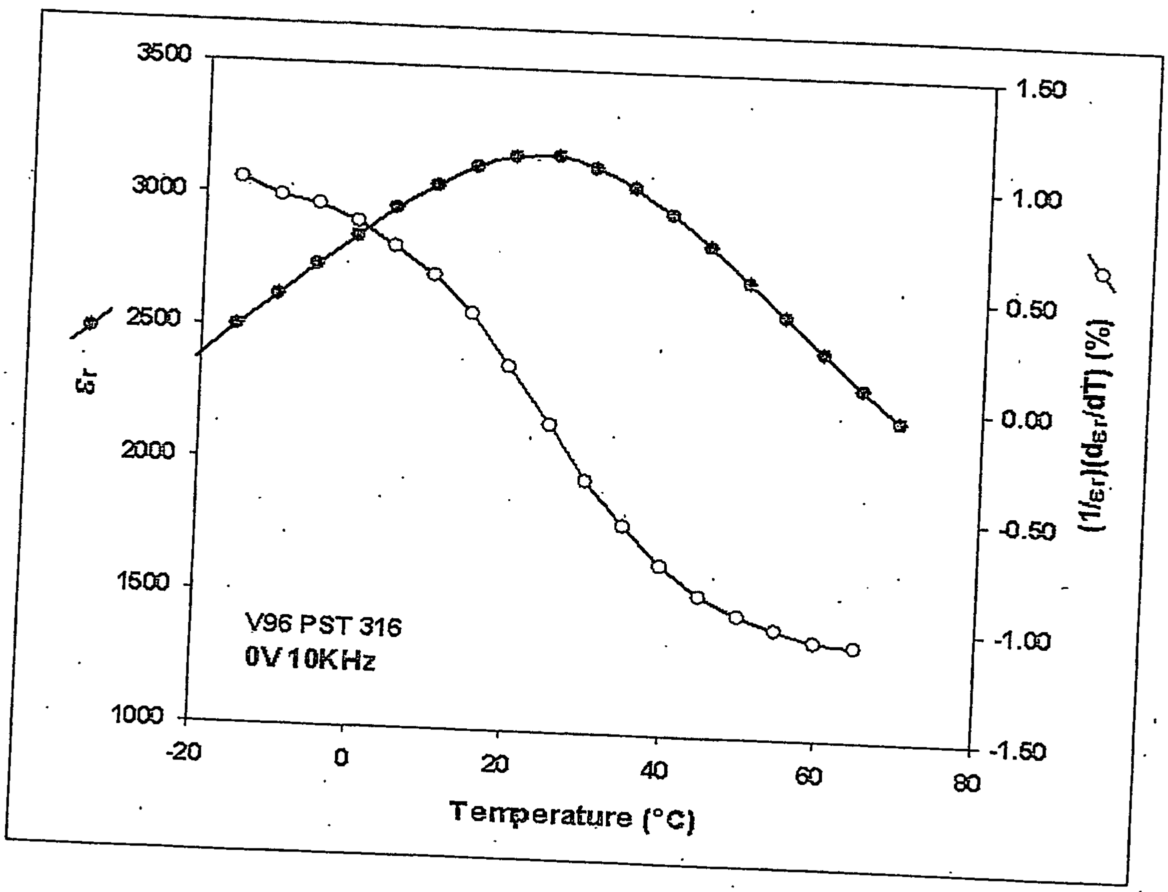


Figure 2



NOT TO BE AMENDED

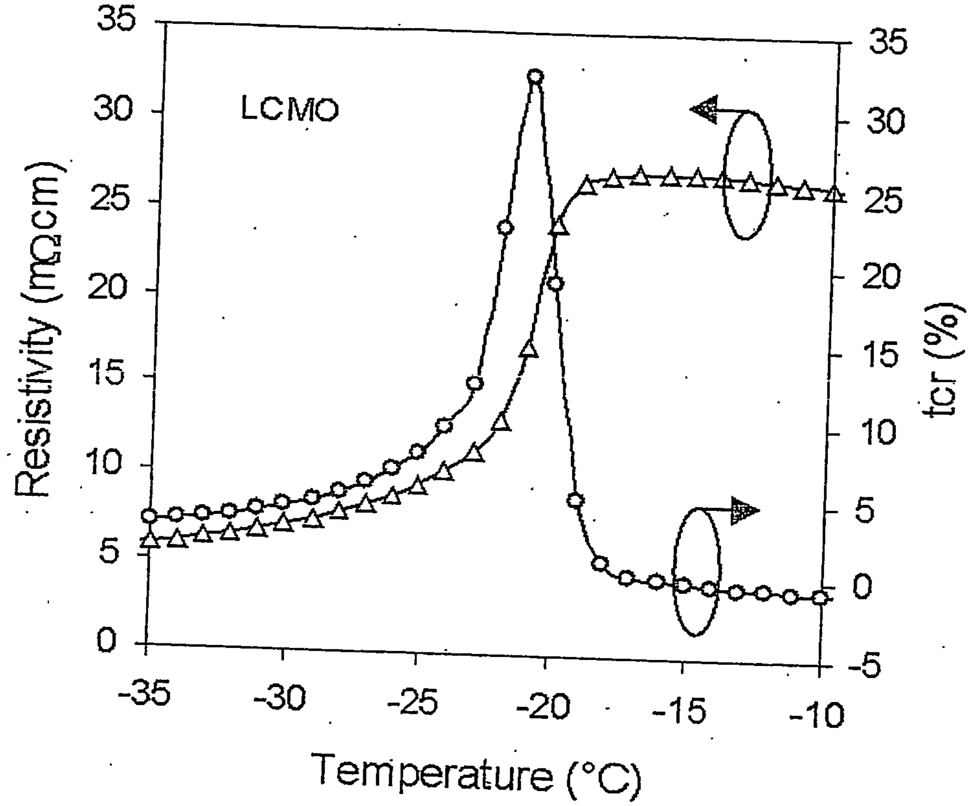
LCMO
Resistivity (mΩcm)
tcr (%)
Temperature (°C)
35
30
25
20
15
10
5
0
-5
-35
-30
-25
-20
-15
-10

**Figure 3**

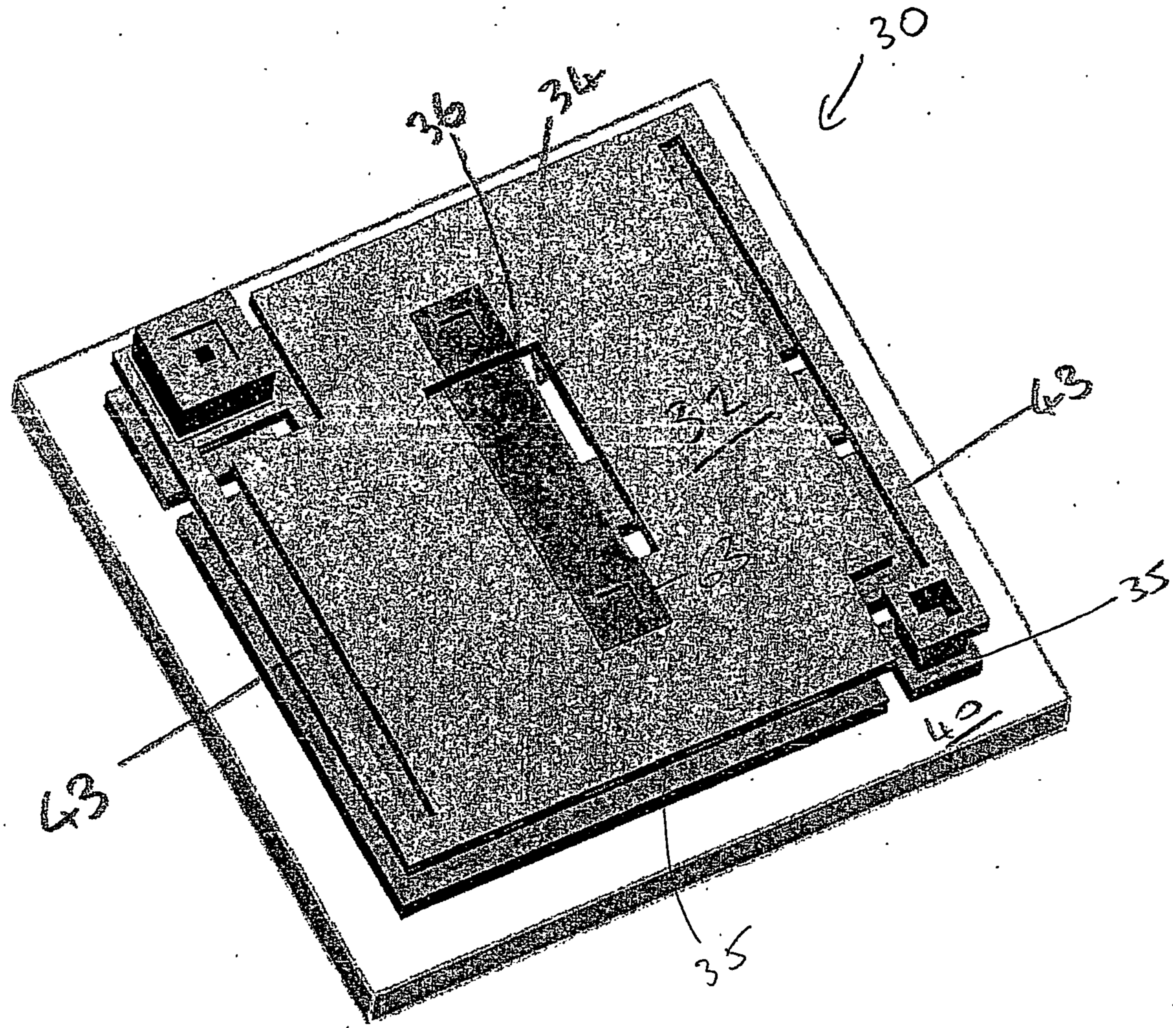


Figure 4



NOT TO BE AMENDED

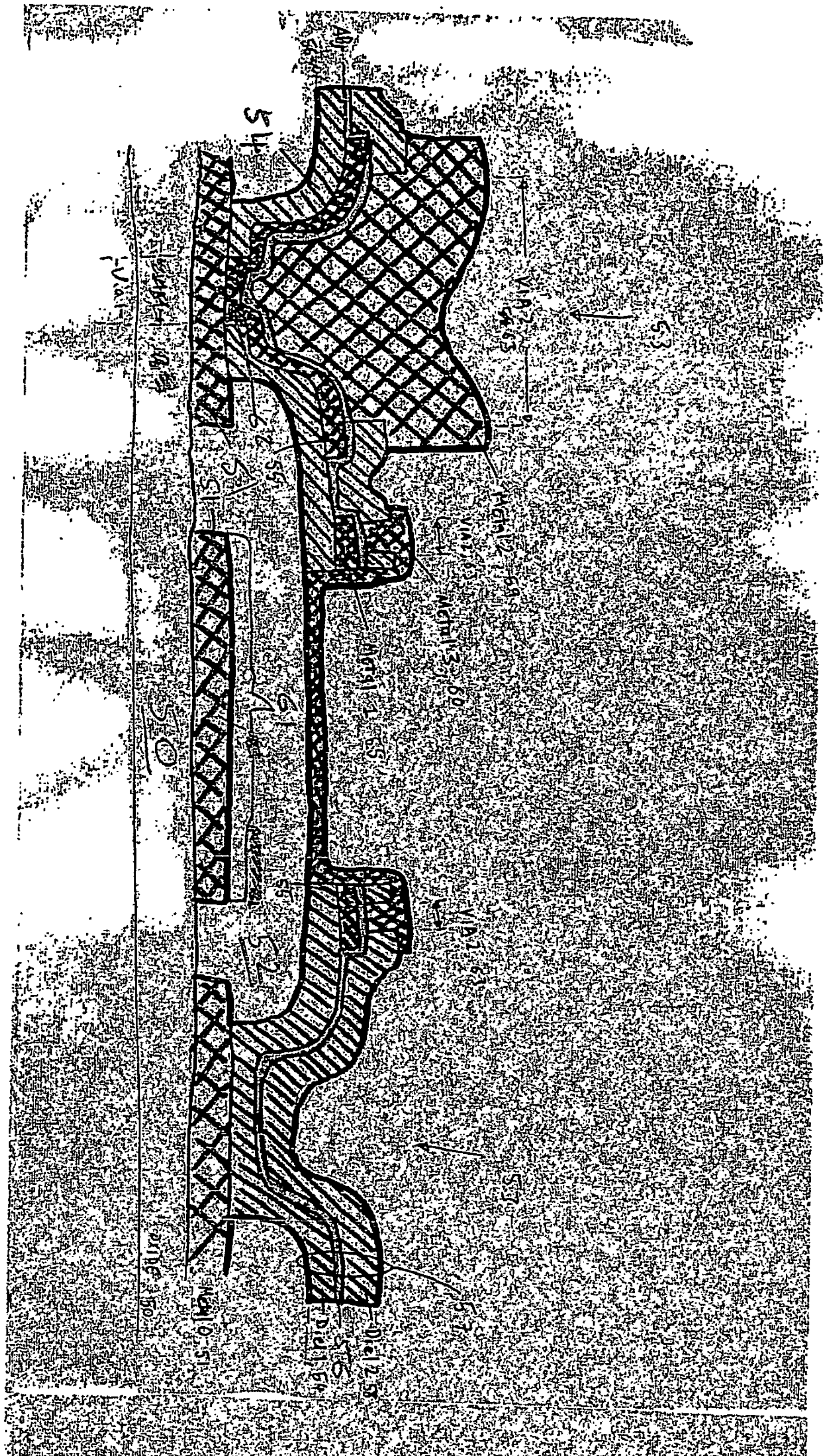

**Figure 5**

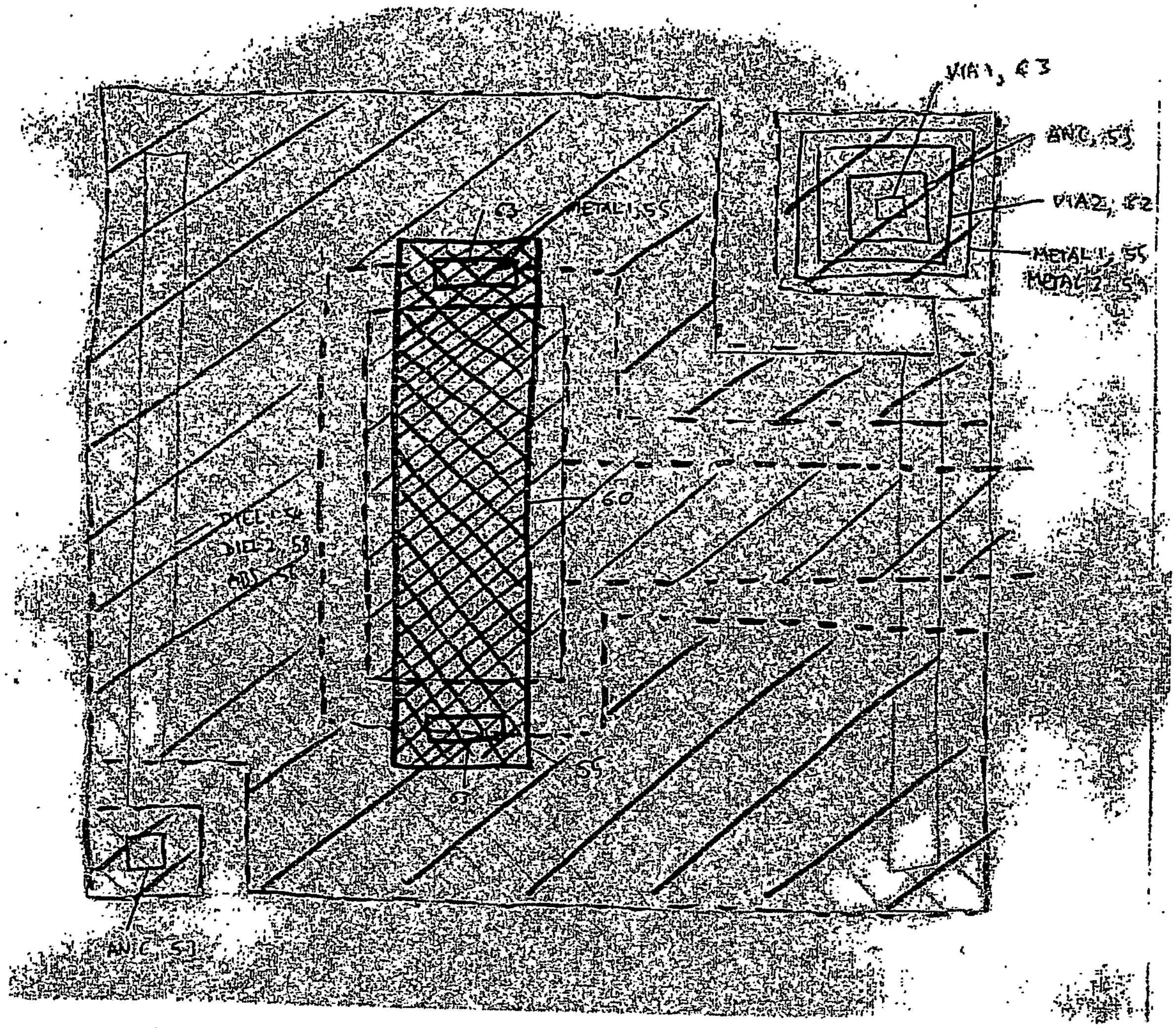
VIA1, 63
ANC, 53
VIA2, 62
METAL1, 55
METAL2, 57
METAL1, 55
60
55
ANC, 53

FIGURE 6

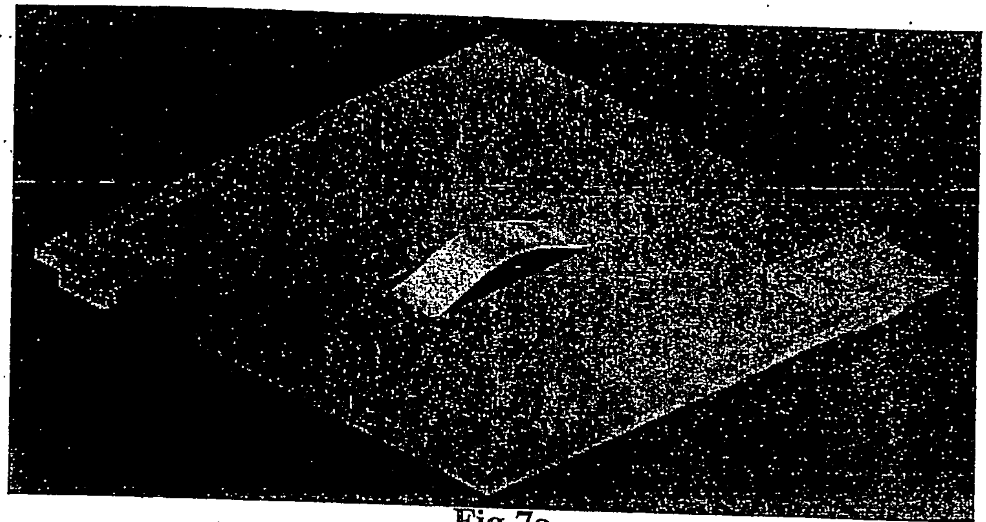

Fig 7a

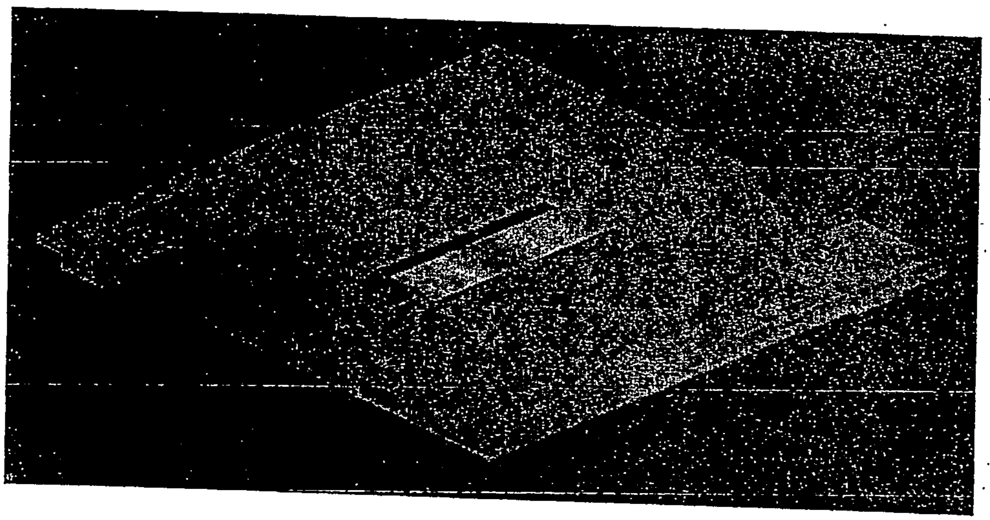

Fig 7b

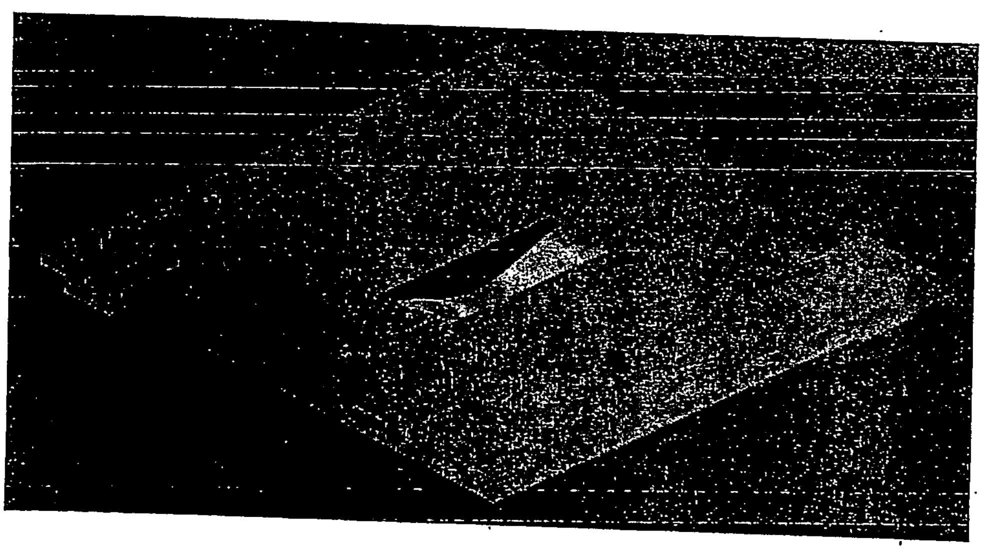

Fig 7c

FIGURE 7

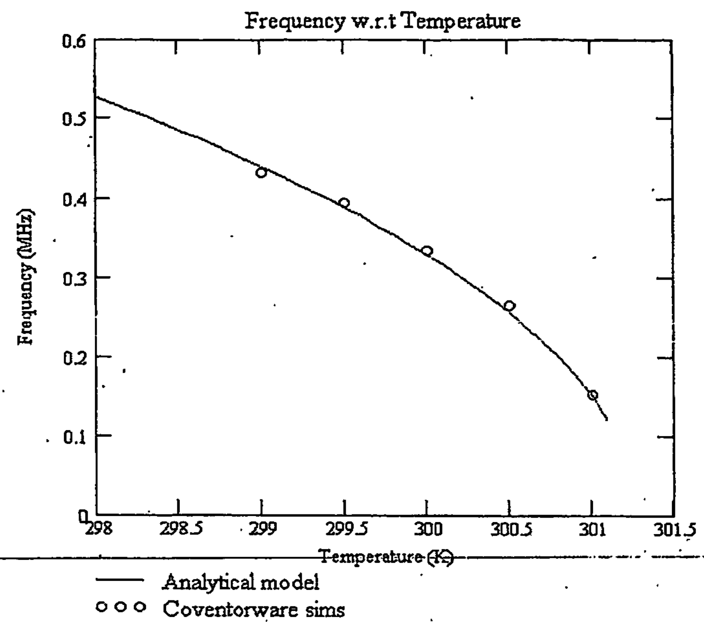


**Figure 8**

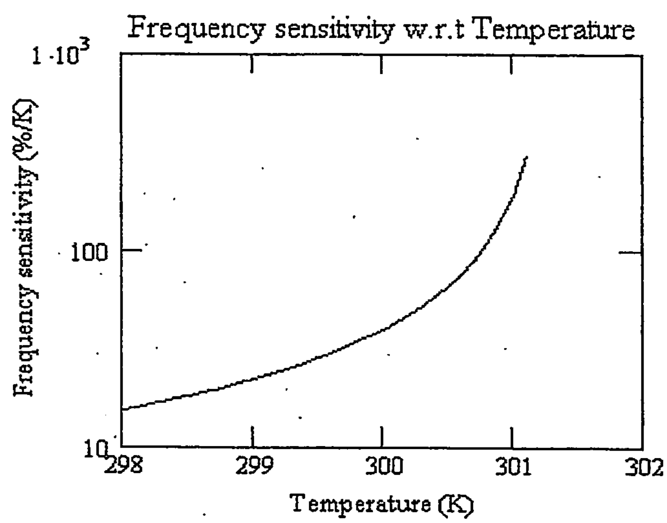


**FIGURE 9**

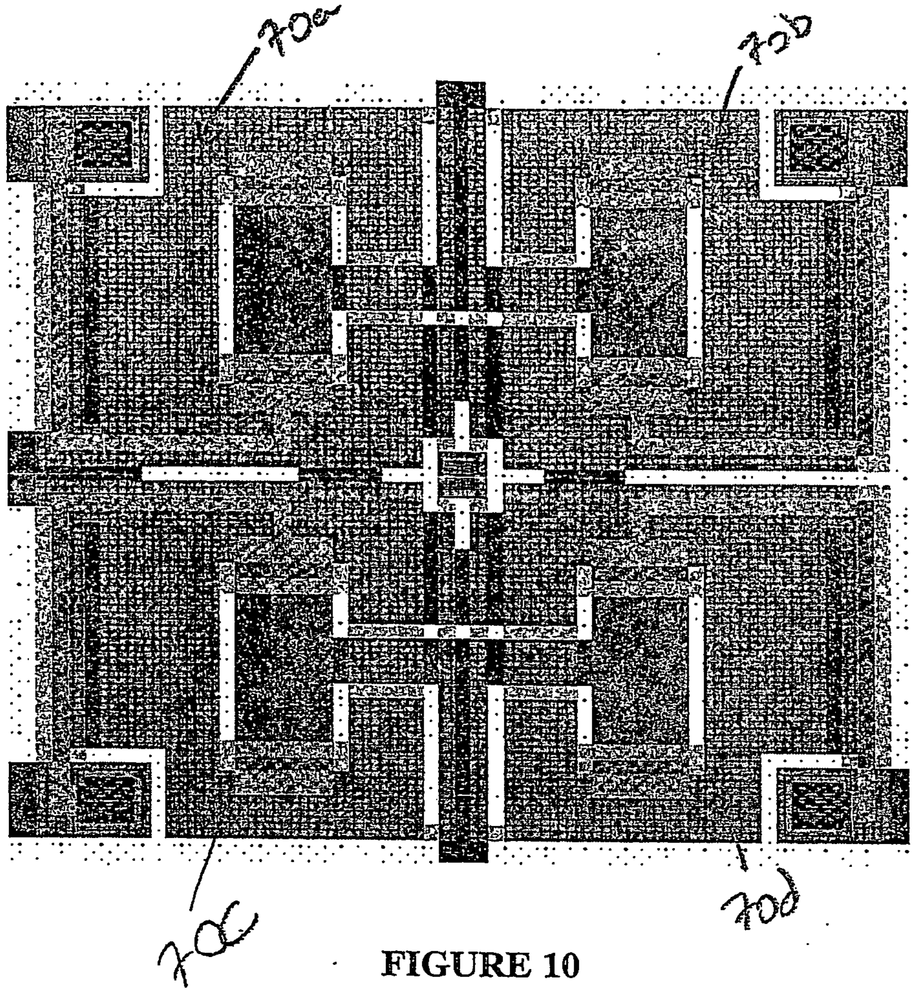


**FIGURE 10**

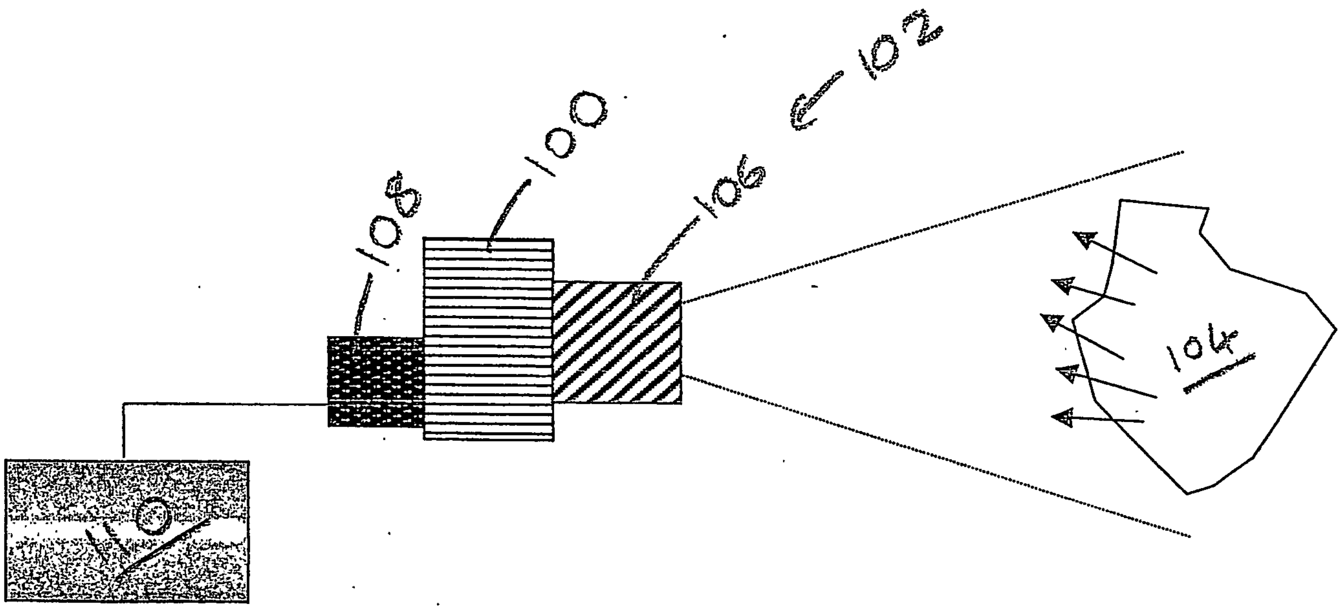


**FIGURE 11**

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